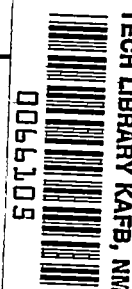# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2975

STRUCTURAL EFFICIENCIES OF VARIOUS ALUMINUM, TITANIUM,

AND STEEL ALLOYS AT ELEVATED TEMPERATURES

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SUMMARY

Efficient temperature ranges are indicated for two high-strength aluminum alloys, two titanium alloys, and three steels for some short-time compression-loading applications at elevated temperatures. Only the effects of constant temperatures and short exposure to temperature are considered, and creep is assumed not to be a factor. The structural-efficiency analysis is based upon preliminary results of short-time elevated-temperature compressive stress-strain tests of the materials. The analysis covers strength under uniaxial compression, elastic stiffness, column buckling, and the buckling of long plates in compression or in shear.

INTRODUCTION

At supersonic speeds, the effects of aerodynamic heating on the strength of aircraft or missiles must be taken into account. The behavior of the materials may prove critical either during transient or during steady heating conditions. The selection of materials having adequate strength under such conditions and at the same time providing a structure having minimum weight becomes a primary consideration.

The effects of steady rather than transient heating are considered herein. An attempt is made to give a general picture of the efficient temperature ranges for a few high-strength aluminum, titanium, and steel alloys for some short-time compression-loading applications in which creep is assumed not to be a factor. The cases covered are strength under uniaxial compression, elastic stiffness, column buckling, and the buckling of long plates in compression or in shear. Some of the materials included, such as the titanium alloys RC-130A and RC-130B, the aluminum alloy XA78S-T6, and the steel Stainless W, are relatively new. The materials cover a wide range of strengths and densities, and the temperatures range up to 600° F for the aluminum alloys, to 1,000° F for the titanium alloys, and to 1,200° F for the steels. The results are based upon tests of compression specimens taken from a single sample of each material and, consequently, should not be considered as necessarily

representative. Besides the materials previously mentioned, those included are extruded 75S-T6 aluminum alloy (data from ref. 1), the steel SAE 4340, and the heat-resistant nickel-base alloy Inconel X. For convenience in making general comparisons, Inconel X is grouped herein with the steels.

TESTS

In order to make the structural-efficiency comparisons for compression loading, compressive stress-strain tests were made. In these tests, the material was kept at test temperature approximately 1/2 hour before the load was slowly applied. The strain rate was maintained at about 0.002 inch per inch per minute during loading. Autographic stress-strain curves were obtained. The compressive test results for Young's modulus and the yield stress (0.2 percent offset) are given in table I along with information on the suppliers, heat treatments, and densities of the materials.

The test results for Young's modulus and the compressive yield stress are given in figures 1 and 2. In figure 1, the variation of Young's modulus with temperature T obtained for these materials is shown. At normal temperatures, the moduli vary from about 10×10^6 psi for the aluminum alloys to about 17×10^6 psi for the titanium alloys and to about 30×10^6 psi for the steels. The moduli for all the materials reduce with increase of temperature. The results for the new aluminum alloy XA78S-T6 are essentially the same as for extruded 75S-T6 aluminum alloy. The heat-resistant alloy Inconel X shows the least effect of temperature.

Figure 2 shows the variation of the compressive yield stress with temperature found for these same materials. The strengths range from about 80 ksi for the aluminum alloys to about 220 ksi for the steels at normal temperatures. With the exception of Inconel X, a marked decrease in strength with increase in temperature is evident in all instances. The aluminum alloys, the titanium alloys, and two of the steels have lost about half of their normal strength at approximately 400° F, 800° F, and 850° F, respectively. Inconel X, a good high-temperature material, shows almost a negligible effect of temperature over the range covered. The results for the two aluminum alloys are essentially the same. Similarly, there is little difference between the titanium sheet and forging alloys. Above about 850° F, Inconel X is the strongest material.

STRUCTURAL EFFICIENCIES

From the results given in figures 1 and 2, together with the use of the stress-strain curves, various structural-efficiency comparisons can be made for the different materials. The comparisons which deal with compression loading are for strength, elastic stiffness, and column- and plate-buckling applications.

Strength efficiency.- In figure 3, the materials are compared on a strength-efficiency basis with the compressive yield stress taken as the criterion for strength. The stress-density ratio, which is equivalent to the load-weight ratio for a unit length of member, measures the efficiency of the material - the higher this ratio, the more efficient the material on a strength-weight basis. With the exception of Inconel X, all the materials are about equally efficient at normal temperatures. The steels and titanium alloys retain this efficiency much better than the aluminum alloys as the temperature increases. Stainless W and SAE 4340 appear to be somewhat more efficient than the titanium alloys RC-130A and RC-130B from about 300° F to 800° F. Inconel X is the most efficient material above about 950° F.

Stiffness efficiency.- In figure 4, the materials are compared on the basis of elastic-stiffness efficiency. Inasmuch as the elastic stiffness of a material is given by Young's modulus, the stiffness efficiency is determined from the modulus-density ratio. Although there is a large spread in the results, the materials all have roughly the same efficiency at normal temperatures. The efficiency for the aluminum alloys, however, decreases rapidly with increase in temperature. At the higher temperatures, the steels are the most efficient, Inconel X being the most efficient material; the titanium alloys are next in order.

Column and plate buckling.- For column buckling and the buckling of long plates in compression or in shear, the structural efficiency for a material at a given temperature is found by a somewhat more complicated method by plotting calculated values of the buckling-stress—density ratio against corresponding values of an appropriate structural index. The method, which is described in reference 2, is based upon the use of the stress-strain curves for the material and covers both the elastic and plastic ranges. Rather than show all these curves for each material and temperature, comparisons are made over the temperature range only for a small and a large value of the index for each application.

The comparisons of the materials for column buckling are shown in figures 5 and 6 for small and large values of the column index $\dfrac{P_{cr}cf}{L^2}$.

In this index, P_{cr} is the buckling load, c is the end fixity, f is

the shape factor, and L is the column length. The efficiency is
given by the stress-density ratio, the stress being the buckling stress
associated with P_{cr}. Figure 5 is for a small value of the index

$\left(\dfrac{P_{cr}cf}{L^2} = 50 \text{ psi}\right)$, which corresponds to a small load or long column. The

aluminum alloys are the most efficient up to about 300° F; from about
300° F·to 900° F, the titanium alloy RC-130B is the most efficient; at
still higher temperatures, Inconel X is the best. Figure 6, for a large

value of the index $\left(\dfrac{P_{cr}cf}{L^2} = 200 \text{ psi}\right)$ corresponding to a large load or

short column, indicates quite a different comparison. In this case, with
the exception of Inconel X, all the materials now have about the same
order of efficiency up to about 300° F. From there up to 800° F, the
titanium alloys RC-130A and RC-130B and the steels SAE 4340 and Stain-
less W have about the same efficiency; above about 950° F, Inconel X
is the most efficient.

The efficiencies of the materials for plate buckling are compared
in figures 7 and 8 in a similar manner for small and large values of

the plate index $\dfrac{P_{cr}k^{1/2}}{b^2}$. In this index, P_{cr} is the buckling load,

k is the plate-buckling coefficient, and b is the plate width. The
efficiency is again measured by the stress-density ratio, the stress
being the buckling stress. Figure 7 is for a small value of this index

$\left(\dfrac{P_{cr}k^{1/2}}{b^2} = 4 \text{ ksi}\right)$ which corresponds to a small load or wide plate. For

plate buckling, the advantages of the lightweight materials are evident,
the aluminum alloys being the most efficient up to about 450° F and the
titanium alloys from there up to about $1,000^\circ$ F. Above $1,000^\circ$ F, Inconel X
is the most efficient. Figure 8, for a large value of the index

$\left(\dfrac{P_{cr}k^{1/2}}{b^2} = 8 \text{ ksi}\right)$ corresponding to a large load or narrow plate, shows

that the same order of efficiency still holds, although the efficient
temperature range for the aluminum alloys is reduced to about 300° F.
Inasmuch as both the efficiency and the index for shear loading are pro-
portional to those for compression loading, the comparisons for plates
loaded in compression also apply to plates loaded in shear (ref. 2).

General comparisons.- The results, which are summarized in fig-
ure 9, indicate in a general way the efficient temperature ranges and
the order of efficiency of the materials for the various comparisons -
compressive strength, elastic stiffness, column buckling, and plate

buckling. For columns and plates, the letters A and B signify small
and large loads, respectively. In this summary, the most efficient
material of each of the classes of alloys is taken as the basis for com-
parisons. For each comparison, three bar graphs are shown: the first
is for the aluminum alloys; the second, for the titanium alloys; and
the third, for the steels. The order of efficiency for each material
is indicated by the degree of crosshatching, the highest efficiency
corresponding to the heaviest crosshatching as indicated. The fol-
lowing example illustrates the use of the figure. If elastic stiff-
ness at 300° F is under consideration, the third bar in the group shows
that a steel is more efficient than a titanium alloy (the second one)
which in turn is more efficient than the aluminum alloys. Without going
into detail in the comparisons, it can be seen that the high-strength
aluminum alloys are as efficient as or more efficient than the titanium
or steel alloys for all applications except stiffness up to about 300° F.
From about 300° F to 950° F, the titanium alloys appear to be superior
for plate buckling and equally or more efficient for column buckling;
these alloys also compare well with steels for compressive strength up
to about 900° F. The steels are the most efficient for elastic stiff-
ness and equally or more efficient for compressive strength over the
entire temperature range; they also are the most efficient above
about 1,000° F for column and plate buckling.

CONCLUDING REMARKS

The comparisons of two high-strength aluminum alloys, two titanium
alloys, and three steels apply only to some short-time compression-loading
applications under constant-temperature conditions and creep is assumed
not to be a factor. The results, which are preliminary and based upon
a limited number of tests, are subject to change depending upon the con-
dition and treatment of the material. The comparisons are also incom-
plete in that no data are included for some magnesium alloys which at
normal temperatures are very efficient for plate buckling or for
24S-T6 aluminum alloy which has definite advantages over 75S-T6 and
XA78S-T6 aluminum alloys for elevated-temperature use. Without con-
sidering the creep aspects, the general indications are, however, that
the aluminum alloys are equally or more efficient for compression-
loading applications for temperatures up to about 300° F. From about
300° F to 900° F, the titanium alloys look very promising. At still
higher temperatures, a good high-temperature heat-resistant alloy is
required to provide a structure having adequate strength and minimum

weight. The final selection of a material for a particular application
will also ordinarily depend upon many additional considerations.

Langley Aeronautical Laboratory,
        National Advisory Committee for Aeronautics,
            Langley Field, Va., May 21, 1953.

REFERENCES

1. Roberts, William M., and Heimerl, George J.: Elevated-Temperature
      Compressive Stress-Strain Data for 24S-T3 Aluminum-Alloy Sheet
      and Comparisons With Extruded 75S-T6 Aluminum Alloy. NACA
      TN 1837, 1949.

2. Heimerl, George J., and Barrett, Paul F.: A Structural-Efficiency
      Evaluation of Titanium at Normal and Elevated Temperatures. NACA
      TN 2269, 1951.

TABLE I

DESCRIPTION OF MATERIALS

| Material	Designation	Received condition	Additional heat treatment	Source of material	Compressive properties and density at normal temperatures		
					Young's modulus, E, psi	Compressive yield stress, ksi	Density, lb/cu in.
Aluminum alloy extrusion	75S-T6	Heat treated by manufacturer	None	Aluminum Company of America	10.5×10^6	78.5	0.101
Aluminum alloy sheet (0.25 inch thick)	XA78S-T6	Heat treated by manufacturer	None	Aluminum Company of America	10.5	81.5	.101
Titanium alloy sheet (0.064 inch thick)	RC-130A	Cold rolled and annealed	None	Rem-Cru Titanium, Inc.	16.2	140.8	.17
Titanium alloy forging	RC-130B	Annealed	Heated to 1,050° F for 1/2 hour to remove machining effects	Rem-Cru Titanium, Inc.	17.7	152.5	.17
Steel sheet (0.064 inch thick)	Stainless W	Solution annealed	Precipitation hardening. Heated at 1,000° F for 1/2 hour	U. S. Steel Corp.	30.2	220.0	.28
Heat-resistant nickel-base alloy sheet (0.064 inch thick)	Inconel X	Annealed	Aged at 1,300° F for 20 hours and air cooled	U. S. Steel Corp.	32.9	115.0	.30
Steel sheet (0.064 inch thick)	SAE 4340	Annealed	Heated at 1,525° F for 10 minutes in controlled atmosphere; air cooled; drawn at 800° F for 1 hour	Crucible Steel Co. of America	30.3	194.0	.283

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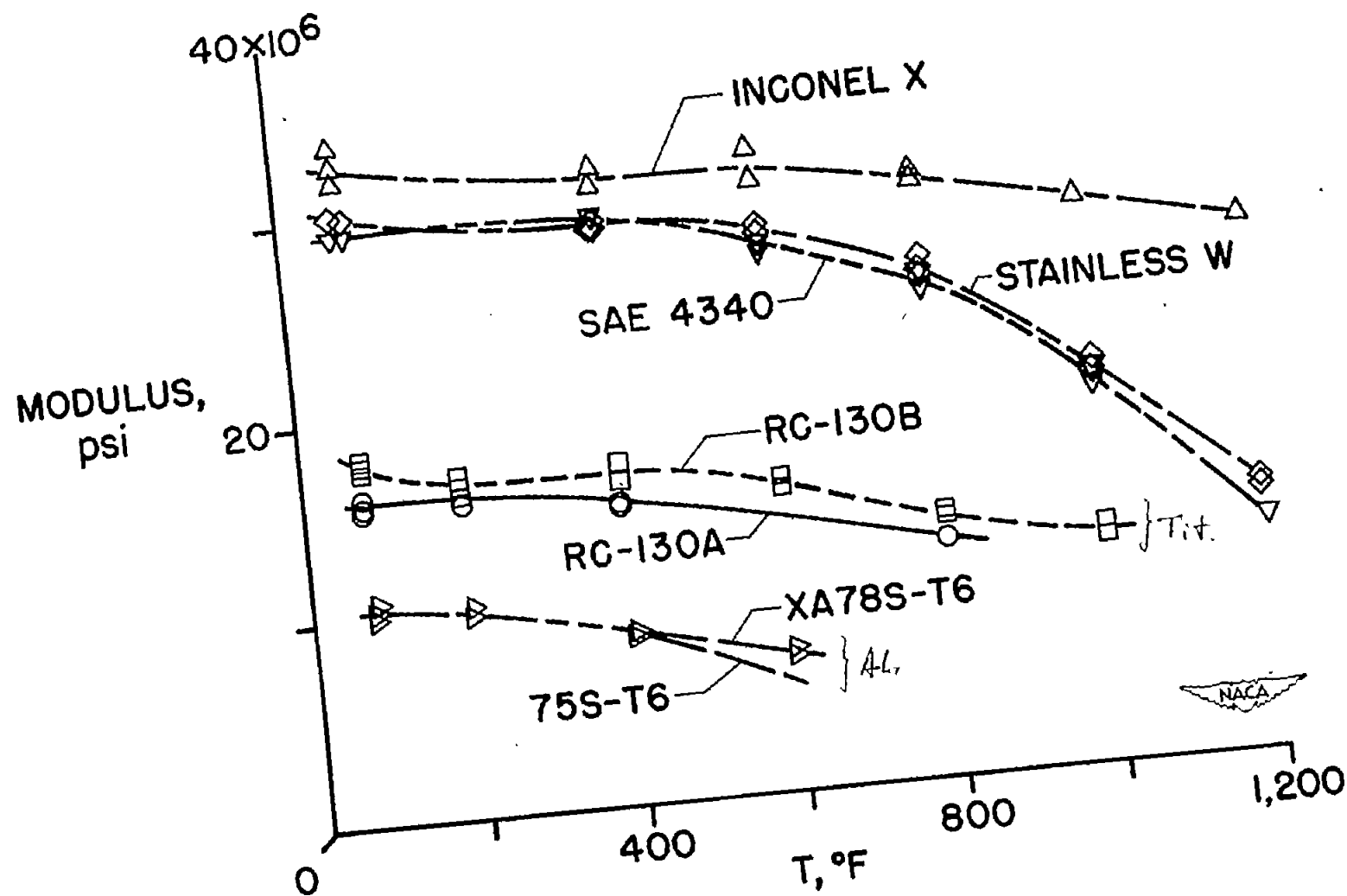
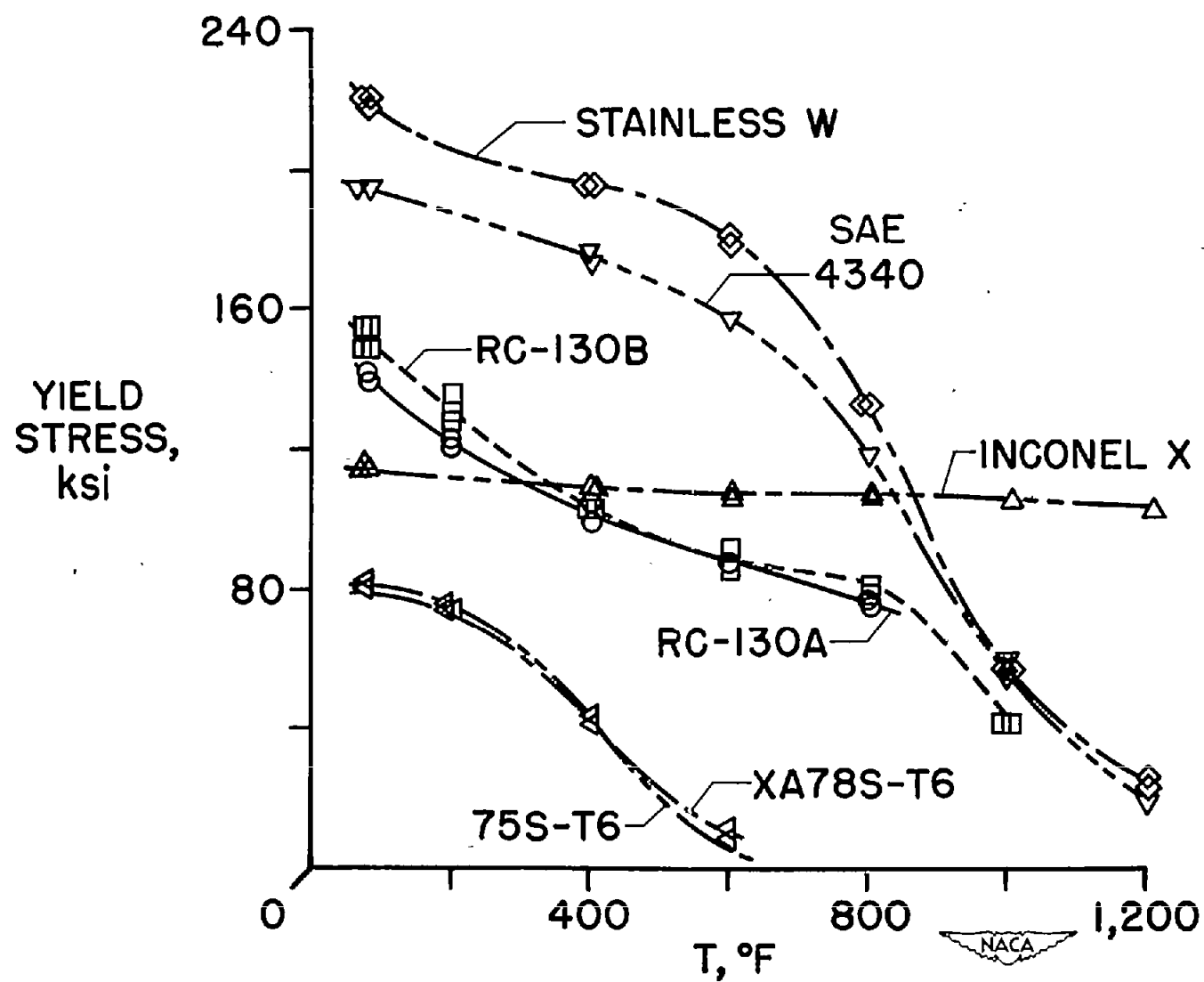Figure 1.- Variation of Young's modulus with temperature.

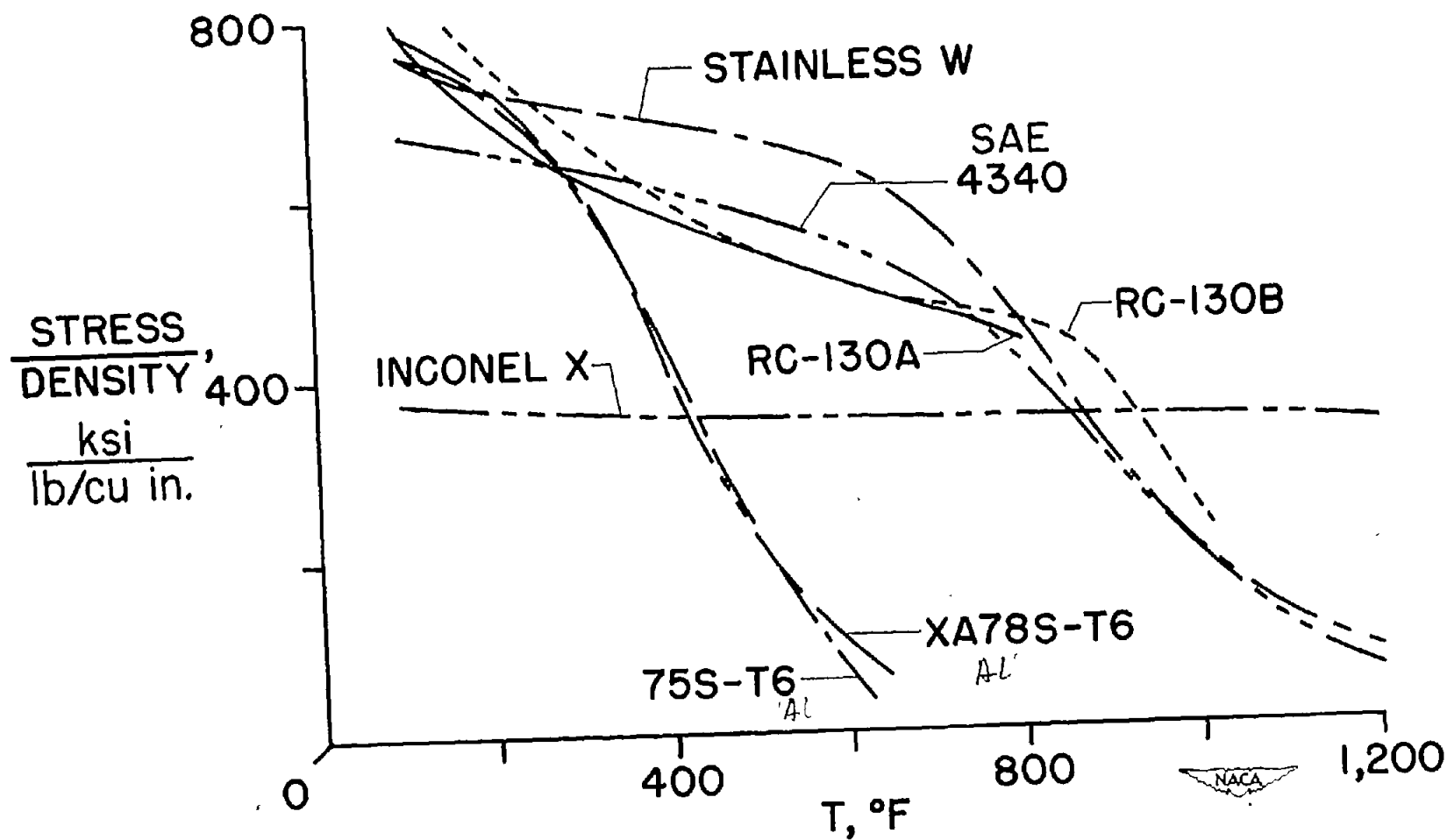Figure 2.- Variation of compressive yield stress with temperature.

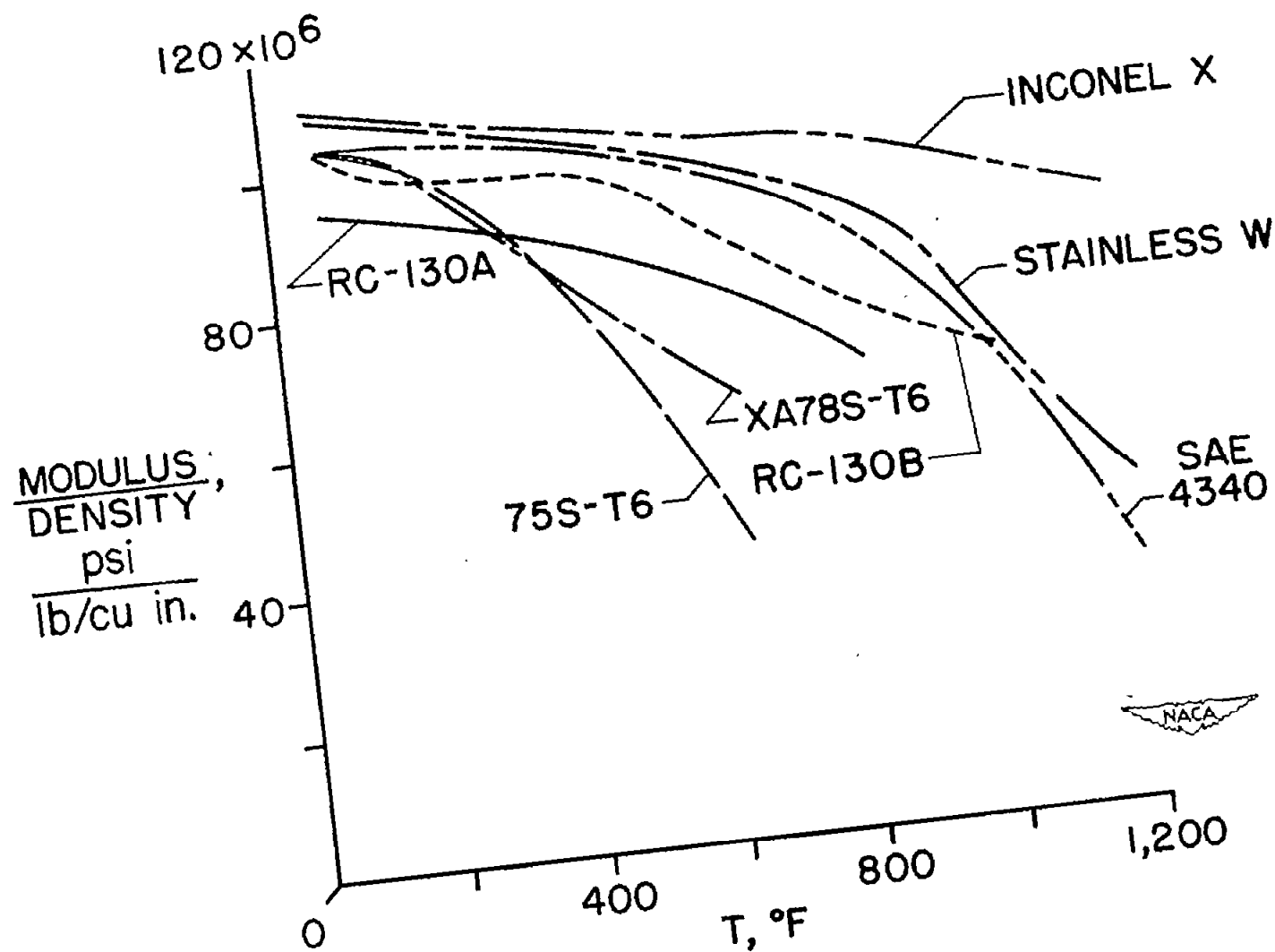Figure 3.- Variation of compressive-yield-stress - density ratio with
temperature.

120 ×10⁶ — INCONEL X

STAINLESS W

RC-130A

80 —

$$\frac{\text{MODULUS}}{\text{DENSITY}},$$

$$\frac{\text{psi}}{\text{lb/cu in.}}$$

XA78S-T6

RC-130B

75S-T6

SAE
4340

40 —

NACA

400   800   1,200

O   T, °F

Figure 4.— Variation of modulus-density ratio with temperature.
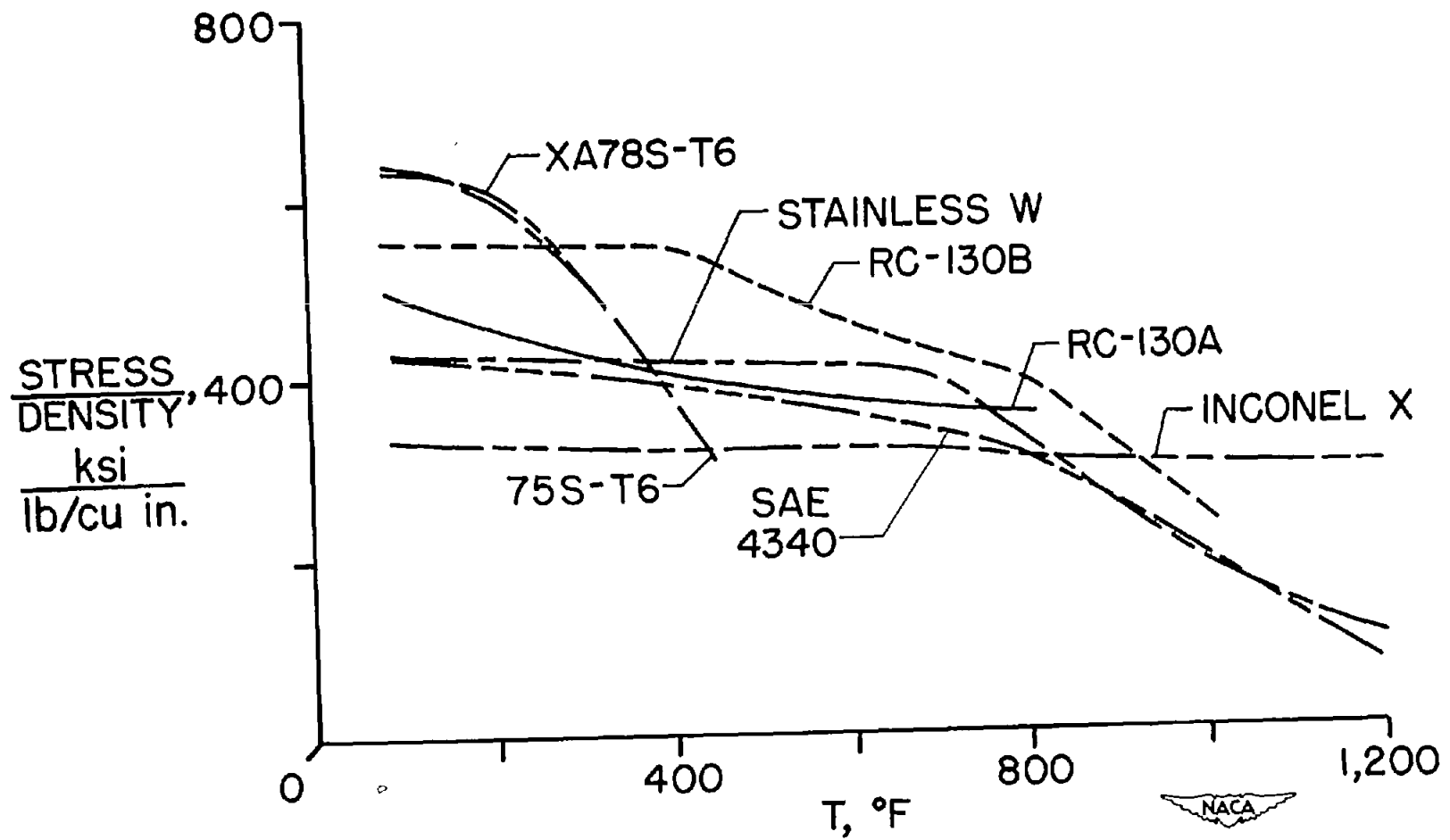
Figure 5.- Variation of column efficiency with temperature.

$$\frac{P_{cr}c^f}{L^2} = 50 \text{ psi.}$$
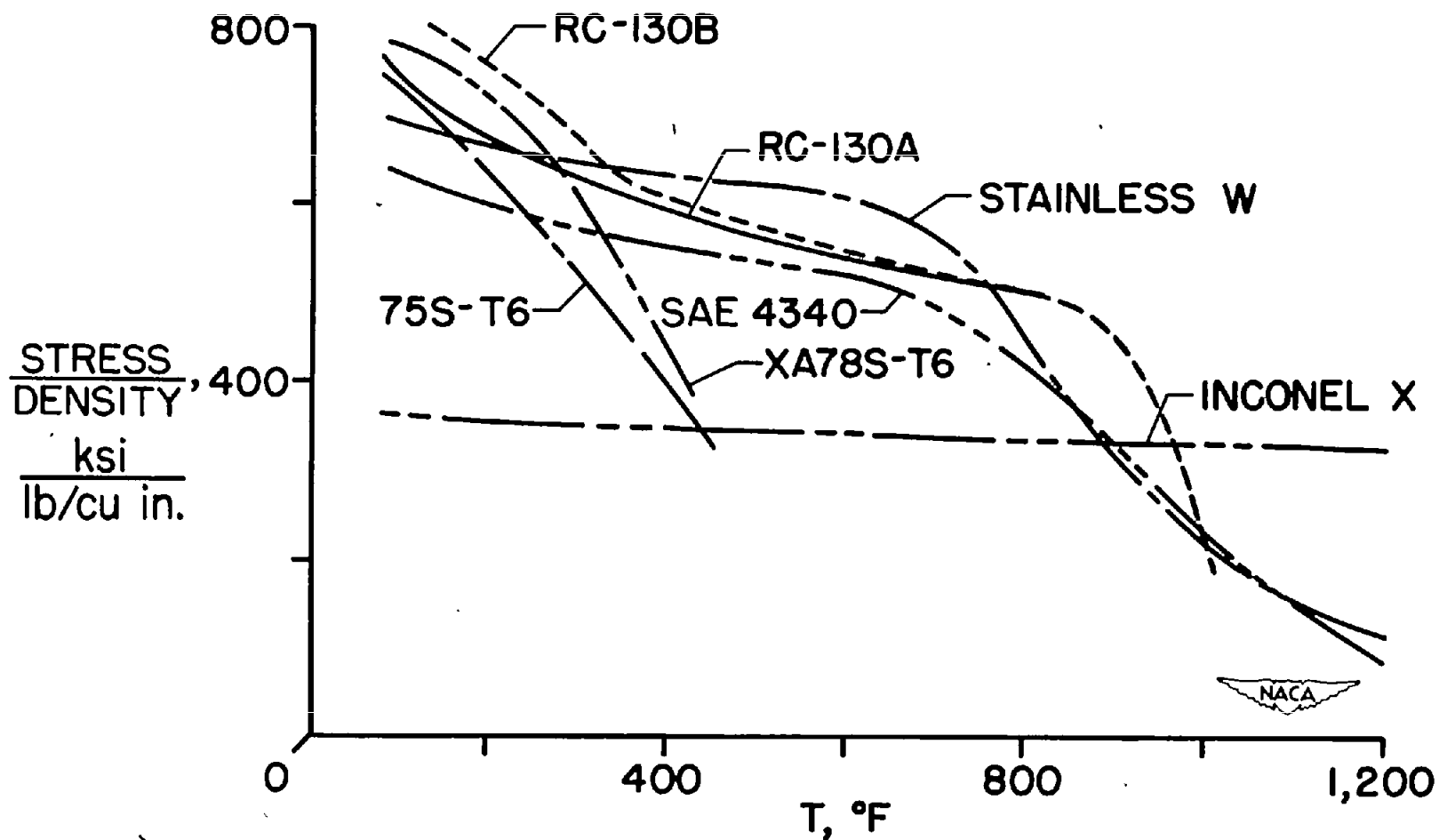
Figure 6.- Variation of column efficiency with temperature.

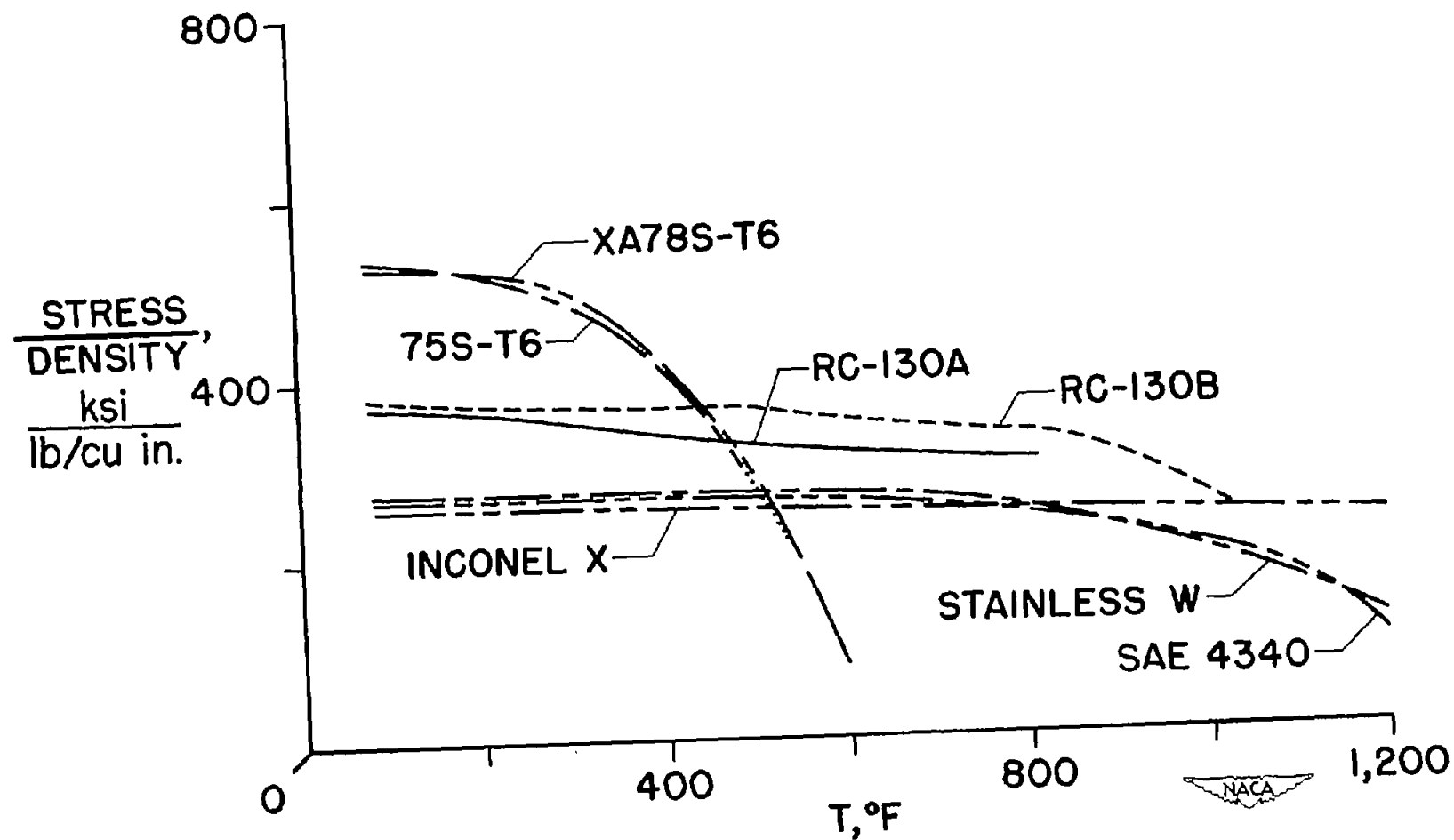$$\frac{P_{cr} cf}{L^2} = 200 \text{ psi.}$$

Figure 7.- Variation of plate efficiency with temperature.

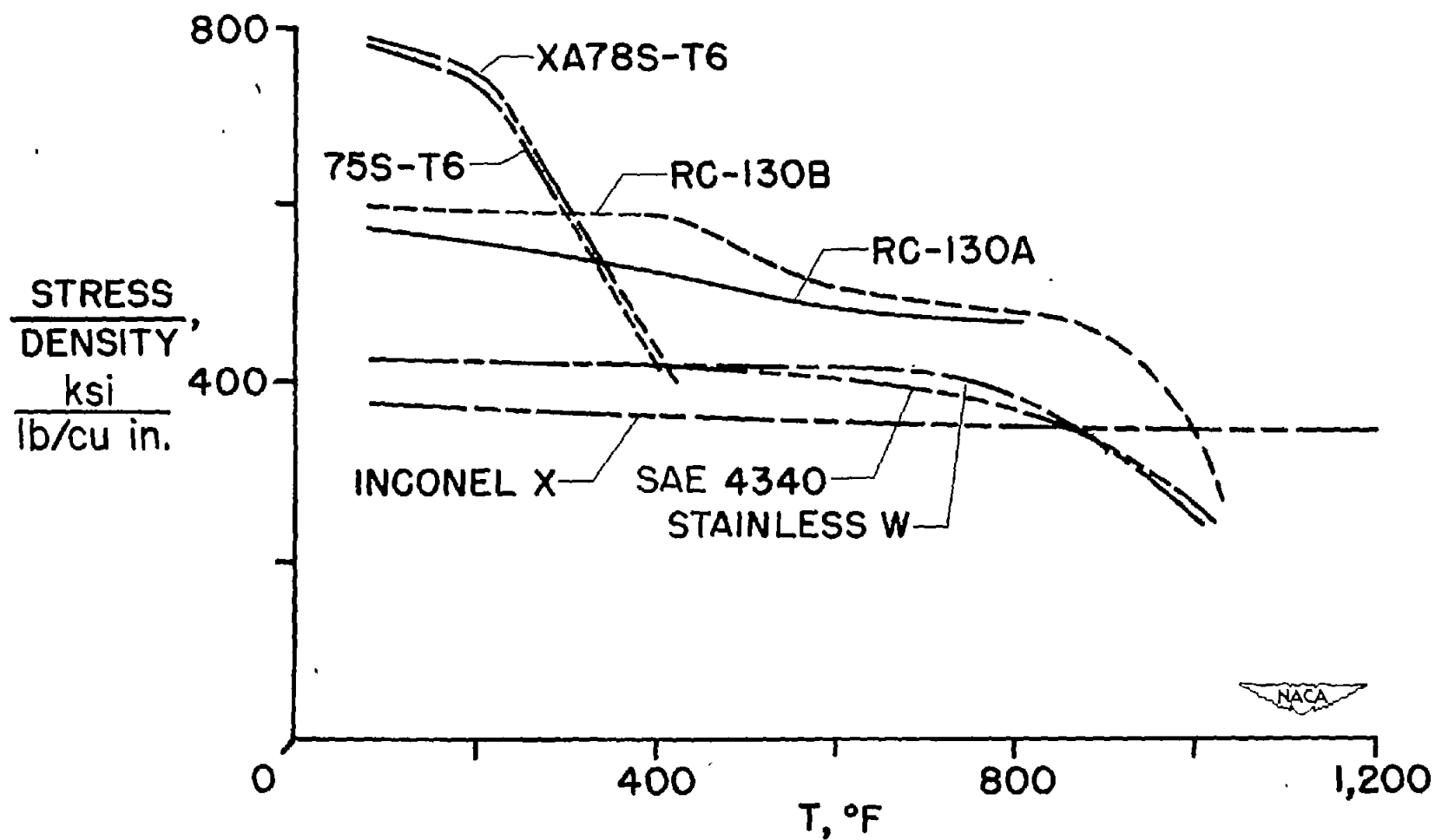$$\frac{P_{cr}k^{1/2}}{b^2} = 4 \text{ ksi.}$$

Figure 8.- Variation of plate efficiency with temperature.

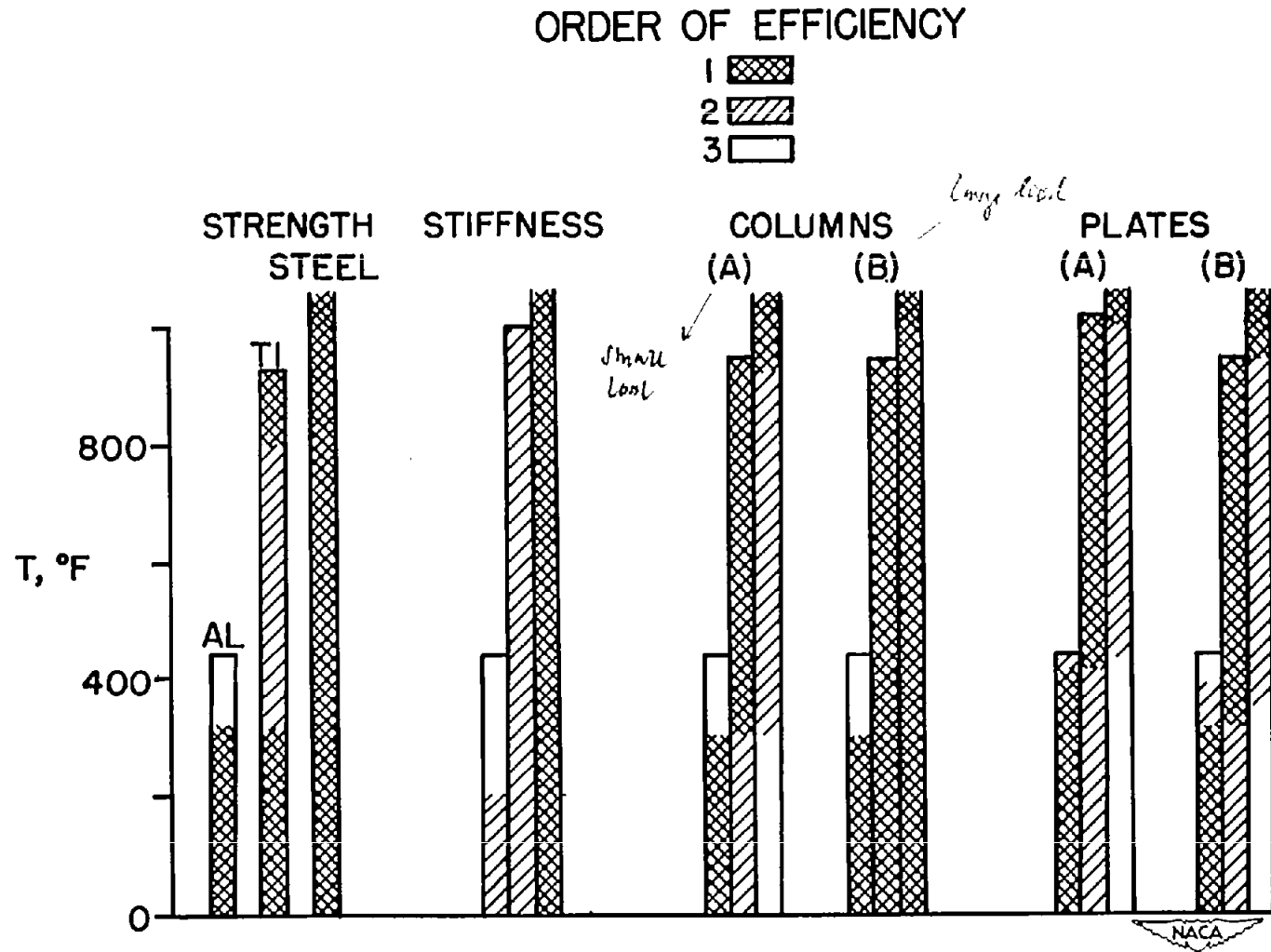$$\frac{P_{cr}k^{1/2}}{b^2} = 8 \text{ ksi.}$$

Figure 9.- Comparison of efficiencies of materials for strength, stiffness, and column and plate buckling. The designations A and B refer to small and large loads, respectively.